Cases of Lightweight Structures for Polar Areas

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Abstract

The paper focuses on what the authors call 'Polar Lightweight Structures'. The first part presents a collection of lightweight structures (LWS) designed and built for Antarctic conditions, with the aim of demonstrating the diversity of approaches attempted by designers. The second part of the paper presents two studies where different computational methods were applied for the design of generic LWS based on the local conditions of two particular Polar locations; namely, the Arctic region and Glacier Union in the Antarctic plateau. Both studies were conducted independently with the aim of demonstrating the feasibility of employing LWS of larger dimensions/scale than currently seen in Polar settings.

Keywords: lightweight structures, Polar regions, structural optimisation, topology optimisation, frame-supported membrane structure, stochastic wind loading.

1. Introduction

Pristine Polar and Subpolar areas have been subject to an increasing demand for the establishment of new settlements in the last two decades. It is only recently that relevant stakeholders have been advising for the need of clearer and more sustainable regulations for Antarctic operators in this matter [1] [2].

Design of large-spanning Polar buildings has become of interest for the architectural and engineering communities in the last two decades, especially in Antarctica. Efforts are being made to provide innovative solutions regarding energy efficiency, indoor habitability, waste management and architectural expression [3]. At the other end of the building spectrum, a broad array of small scale LWS can be found in the form of tents and shelters. These structures represent remarkable examples of structural efficiency and minimal environment impact strategies while enduring one of the harshest climate zones. However, the use of LWS in larger scale has not been sufficiently explored. The authors propose that medium and large scaled LWS can be introduced effectively in Polar settings by applying novel computational design and analysis methods. Since practically all building materials need to be transported to construction sites in Polar Regions, the optimisation of the used material plays a key role in the sustainability of such project. This type of construction can contribute to minimise the potential environmental impact derived from new infrastructure demand in pristine cold environments.

2. Evidence

As part of a research project conducted by University of Bath, evidence of lightweight constructions purposely designed for Polar settings was collected [4]. Despite the diversity observed, it can be said they all correspond to cases of single or doubly curved structural surfaces.

The array of structural surfaces was organised into two main groups: rigid and non-rigid systems, as proposed by M. Betchold [5]. Rigid surfaces, including one-way systems (vault-like and beam-like systems) and two way systems (shells and gridshells). Non-rigid structures include mechanically and pneumatically pre-stressed membranes. Combinations of these groups are also possible (either hybrid or freeform arrangements).

Several examples of rigid surfaces designed for Polar conditions could be found. Some of the best-known cases of large-spanning structures is the Amundsen-Scott Dome, a 50m geodesic shell built with bolted aluminium bars for the U.S.A National Science Foundation [Fig. 1(a)] [6]; while examples of small isolated units are represented by the Igloo Satellite Cabin©, known as the 'Apple Hub', a small-scale semi-monocoque rigid shell created for the Australian Antarctic Division in 1980. A modified version of this type was later created, allowing the combination of vaulted and synclastic rigid panels [Fig. 1(b)] [7]. Hybrid approaches have also been attempted; such is the case of the Schockwave Tent (ARQZE Architects) in 2002 to serve as an aircraft hangar in Antarctica [Fig. 1(c)]. The surface can be described as an ellipsoid's section formed by a trussed aluminium shell covered by a membrane. This project lasted three years in service before collapsing.

Examples of gridshells can be found in Southern vernacular dwellings, as documented by R. Casamiquela [8]: the Kaweshkar dwelling consisted of a flattened dome with elliptical base, approx. 3 by 2m, formed by a quadrilateral grid of flexible wooden rods covered by seal skin [Fig. 2(a)]. A more complex example is represented by the Aonikenk case, which consisted of a half-ellipsoidal gridshell capable to be employed in different arrangements. While a uni-family unit has been described to be 3-5m wide, 2m high at the front, and 2-3m in depth; a larger model used in Northern Patagonia has been described as capable to host up to 50 people measuring 12m in diameter and 5m high at the centre. The structure also consisted of a quadrilateral grid supported by vertical poles placed in a regular fashion with a Guanaco-skin cover sewed onto it. These structures could be used by its own with an open façade [Fig. 2(b)], aggregated to another unit to form an elliptical dome [Fig. 2(c)], or with an auxiliary membrane structure [Fig. 2(d)].

Figure 1: (a) Amundsen-Scott dome, image: Andy Martinez, 2009; (b) The 'Melon Hub', source: Icewall Ona, 1998; (c) The Shockwave Tent, image: ARQZE, 2010.

Examples of non-rigid surfaces designed for Antarctic purposes were also identified. Cases of membrane structures included the ETPAT Station in Patriot Hills. This was built in 1999, and consisted of a 50m long membrane-tunnel. Anticlastic membrane sections were fastened to steel arches of 4m diameter placed in a radial disposition [Fig. 3(a)]. A revision of this structural concept was used by the design team, ARQZE [9], to create a small-scale unit in 2000 [Fig. 3(b)], the Sastruggi Room, this time using aluminium arches. The surface was formed by nine membrane segments and it was designed either to stand independently, to be replicated along its three axis to form larger units, or to be grouped to other structures. The 'In the Footsteps of Scott' tent is another case of a small-scale membrane structure from 1985. The British Antarctic Survey commissioned a new and lighter version of the original pyramidal tent used by Robert F. Scott in his expedition to the South Pole. The solution from Buro Happold designers was to optimise the original volume towards a

more dome-like body, for which a semi-deployable umbrella-system consisting of six glass-fibres bars contained by a doubly curved faceted volume was proposed [Fig. 4] [10].

Figure 2: (a) Kaweshkar Dwelling. Source: Mediateca Chile, undated; (b) Tehuelche dwelling, image: E. Gerreaud, 1900; (c) Semi-spherical model of a Teheulche deweeling, source: Archivo General de la Nación Argentina, 1969; (d) Asymmetrical tent model of a Tehuelche tent, source: E. barberia, undated.
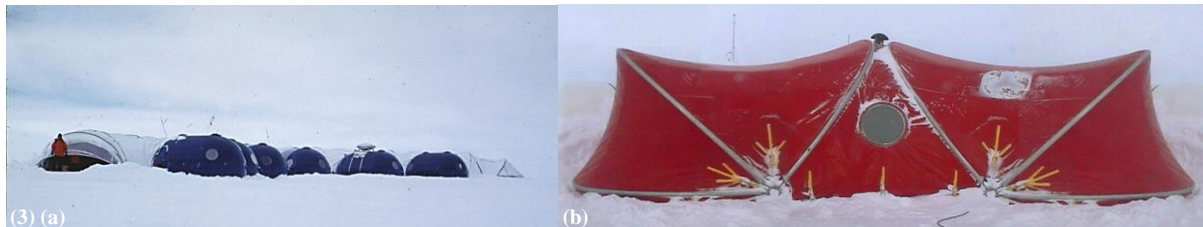

Figure 3: (a) The EPTAP, image: P. Serrano, 1999; (b) Sastruggi Room as part of the EPTAP Station, Antarctica, image: ARQZE Architects, 2000.

Figure 4: BAS Antarctic Expedition Tent, image: Buro Happold, 1985.

3. Cases of Polar LWS using computational design methods

3.1 Structural Optimisation for an Antarctic Lightweight System

This case corresponds to a design-led study conducted by University of Bath using Glacier Union as the location for a new scientific research station. An early-based scheme was used in this study. This consisted of a frame-supported membrane structure formed from a set of 2D elements, arches of variable span, braced by a cable net in a triangulated fashion [Fig. 5(a)]. The structure should be 28m long and its diameter varied from 4 to 10m. Rigid elements were considered for lateral support to be placed at the tunnel's ends, as well as at intermediate distances. Preconditions for the application of

this scheme in Antarctica included: i) minimal weight, ii) minimal number of different components, iii) possibility of expand or modify the overall geometry and, iv) mechanically unaided assembling.

Due to purposes of optimisation, different options of trussed arches using carbon fibre bars and aluminium joints were compared [Fig. 5(b)]. Target parameters were deformation and combined normal stresses. Material properties at this stage were disregarded. Model 2 was the chosen option due to structural and constructive advantages. Characteristics snow and wind loads were applied as nodal forces on joints and included linear SLS and ULS combinations.
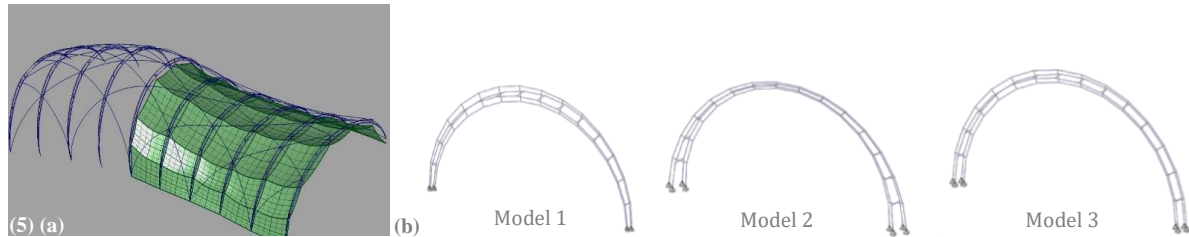

Figure 5: (a) Early scheme for an Antarctic structure, (b) tested versions of trussed arches.

A second step involved a sensitivity study where the influence of different geometry attributes needed to be established. Attributes included mid-span depth, number of subdivisions/joints, bars' cross section, joints' cross section, and joint geometry. Material properties were considered at this stage. The distance between arches (or gap) was fixed at 1m. Due to the numerous variables to be studied, this was defined as multi-objective structural optimisation problem.
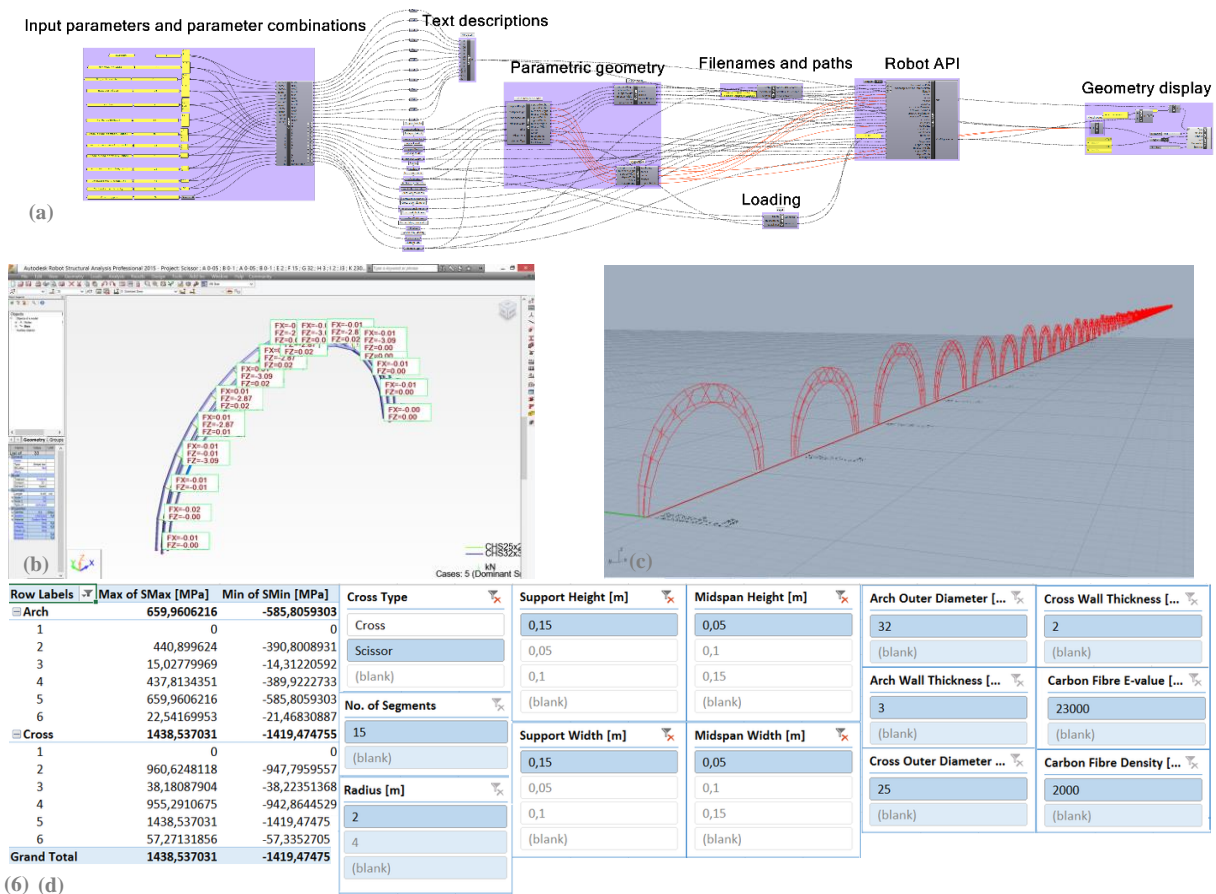

Figure 6: Components of custom software: (a) parametric pipeline, (b) geometry variations, (c) automatically generated FE-model, (d) presentation of results in Excel.

4

Traditional FEM methods quickly probed impractical. Therefore, a software tool was developed, which allowed the interaction between a parametric CAD environment (Rhinocero's Grasshopper), capable of producing the multiple versions of the 2D elements, and a FEM software tool (Autodesk's Robot Structural Analysis) to examine each element. This interaction was possible by using a bespoke object-oriented programming component (Microsoft's C-Sharp). The resulting output files were combined to a single file formatted automatically by using Power Query for Excel©, to take advantage of Excel built-in functions such as pivot tables, filters and slicers to organise the data and easily compare hundreds of different geometry variations [Fig. 6].

This approach allowed for nodal forces to be generated parametric based on each elements dimension [Fig. 7(a)]. Additionally, arches could be discretised by almost straight segments, which curvature was controlled in order to reduce pre-stress [Fig. 7(b)].

As a result, the 'partial structural optimisation' was used. This approach implied that variations of each geometrical parameter were limited to a certain number of options for the entire range of arches span possibilities. The number of different options was determined based on the sensitivity of the given attribute on the resulting stresses, and material capacity. Due to the necessity of limiting the number of different components, the option for arch span was limited to integer meter values. By using C-Sharp, the distance between arches could also be automatically adjusted according to the bearing capacity of two neighbouring arches, this is, the loaded area assigned for each arch type. The resulting values obtained from the grouping strategy are displayed in Table 1.
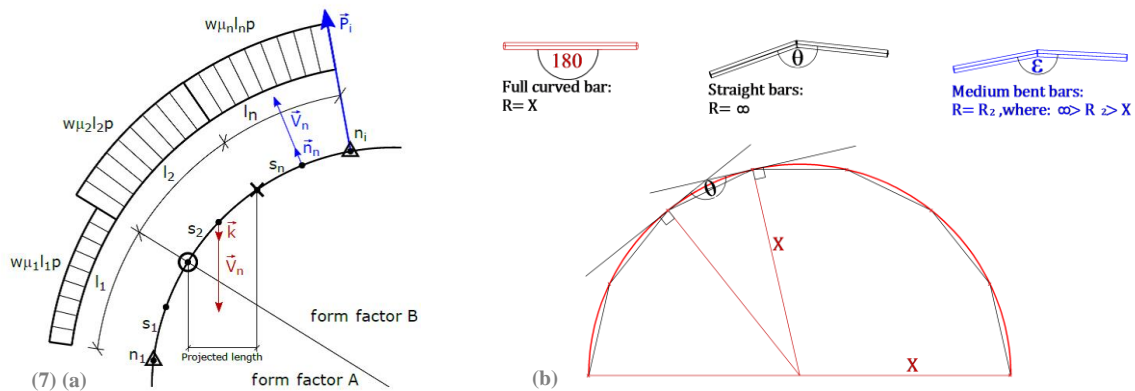

Figure 7: (a) Diagram of geometric attributes for calculation of nodal forces, (b) angle between an arc's segments according to different level of curvature.

Table 1. List of components and attributes' values.

Group	1			2			3			4		
Span range	$12 \leq S \leq 10$			$10 \leq S \leq 8$			$8 \leq S \leq 6$			$6 \leq S \leq 4$		
Arch's mid-span depth [mm]	500			400						300		
Arch's bar rod section (OD/WT) [mm]	40/5			35/5			30/5			25/5		
Archs' Number of subdivision	12			11			10			9		
Archs' Span [m]	12	11	10	9.9	9	8	7.99	7	6	5.99	5	4
Distance to neighbour arches [m]	1.2	1.43	1.67	1.23	1.5	1.77	1.71	1.95	2.2	1.3	1.81	2.4

Additionally, the reduction of number of different joints could be explored independently and the solution could later be integrated to the parametric model. This consisted in adding a small degree of tolerance in the length and the rotation of the elements' design [Fig. 8(a)]. With this strategy, the number of joints for the whole range of arches was reduced from 24 to 7 variations.

Figure 8(b) shows an example of mapping of component types and Figure 8(c) shows some examples of surfaces structures implemented with the model.
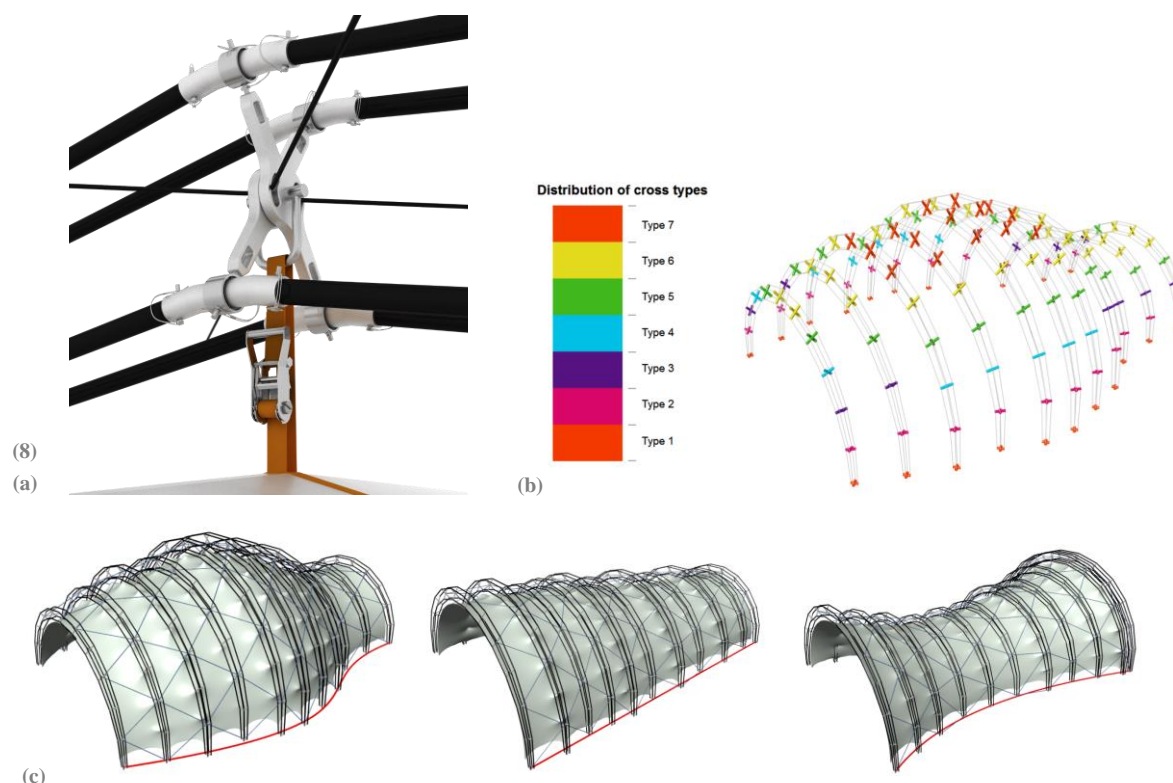

Figure 8: (a) Bespoke aluminium joint, (b) mapping of different types of joint in a surface, (c) examples of parametric models with different surfaces.

3.2 Weight minimisation through topology optimisation

This research project was conducted at DTU Civil Engineering. The design of lightweight structures can be supported and inspired by using topology optimisation (TO), a mathematical method, which can solve complex design problems within a defined domain. By minimising the compliance, such the external work equations [11] of a finite element method (FEM) computation [12], the process is capable of estimating optimised structural layouts by the solid isotropic material with penalisation (SIMP) approach [12] [13] and deliver an architectural usable design. Here, a Matlab-based TO code presented in Sigmund [14] was used.

In Polar regions, high characteristic wind speeds [15] lead to dominant extreme wind loads. For the design of lightweight structures, the description of the loading process is important to adapt and optimise the load carrying system. To this end, a wind tunnel study was performed in the closed-circuit boundary-layer wind tunnel at DTU Civil Engineering on a half-circular shaped model typical for habitats in remote Arctic regions [Fig. 9]. These structures consist usually of membrane covered arched frames.
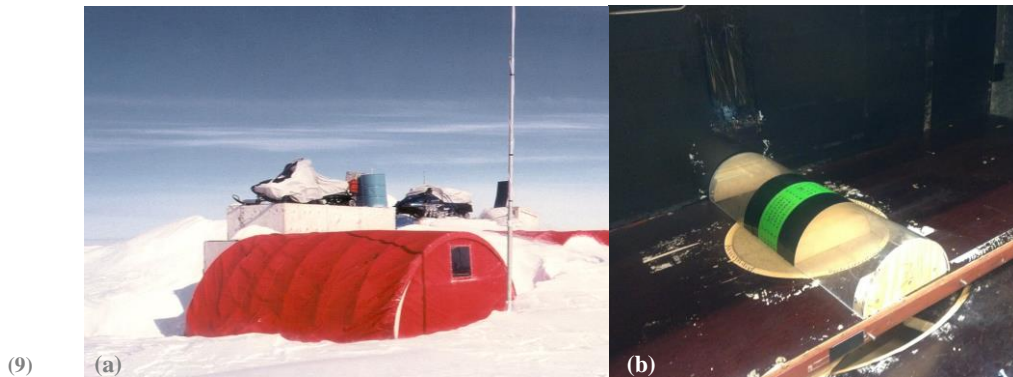
Figure 9: (a) Shelter structure for research activity on the Greenlandic ice sheet, Image: J. Maurer, NSIDC; (b) Wind tunnel model setup in test section.

3.2.1 Measured pressure distributions

The wind tunnel experiments have been carried out on a half cylindrical shaped model of 15cm diameter spanning over the width of the wind tunnel to achieve a two-dimensional flow condition [Figs. 9(b) and 10]. The pressure distribution along the model's arch was measured over an influence width (IW) of $\frac{1}{3}D$ [Fig. 11]. Hence, the test setup focuses on the load process on the 'inner' part of the building (end effects neglected).
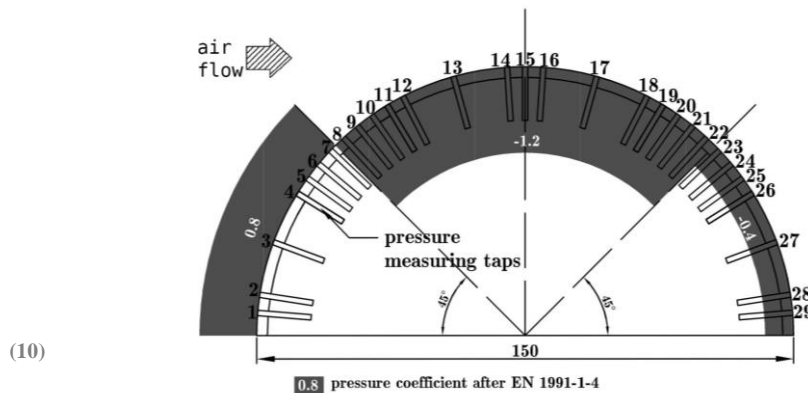

Figure 10: Cross section AA of building model with curvature diameter of D=150mm. Pressure tap arrangement based on pressure distribution based on [16].
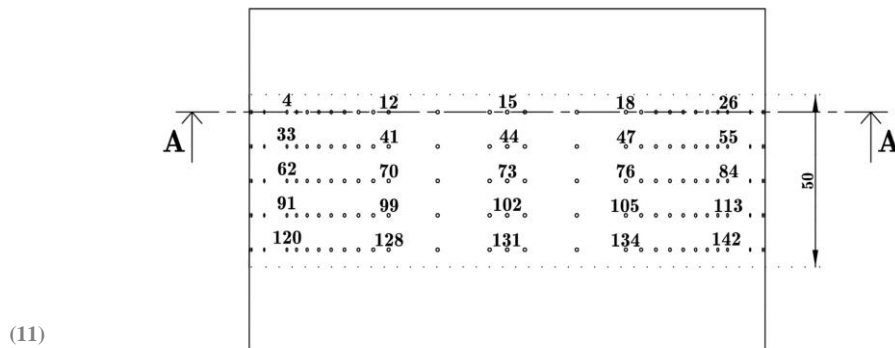

Figure 11: Top view of model with IW of $\frac{1}{3}D$=50mm for wind load integration.

The wind loads were recorded at six different reference air speeds between 2 to $25\frac{m}{s}$ (Re ~20,000 to 250,000) measured at model height, i.e. 75mm above wind tunnel floor with a sampling frequency of 750Hz over 60 seconds. Simulating wind load on an arched geometry at reduced scale requires careful considerations of scaling effects. Figure 12 shows the over IW integrated mean pressure coefficients over the arch, normalised with the reference air speed squared. As expected, the distributions measured at wind speeds above $10\frac{m}{s}$ show a higher consistency to each other compared to the results recorded at lower wind speeds. However, in frame of this study all results have been considered disregarding possible scaling aspects to provide a wider range of wind load scenarios as input for the structural optimisation.
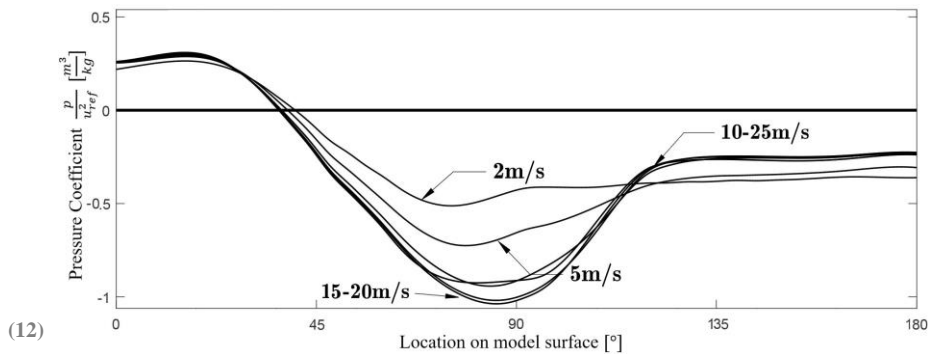
(12)

Figure 12: Mean pressure coefficients for various wind speeds at model height.

3.2.2 Application on topology optimisation algorithm

The normalised mean pressure coefficients averaged over both, IW and recording duration were applied. The corresponding TO results for the frame structure [Fig. 13] show a clear response to the distribution characteristic of the applied load conditions [Fig. 12]. In this case, the support restrains were spread over the entire 'ground floor' in vertical and horizontal direction corresponding to the solution space. For the calculations, an isotropic material with unified elasticity modulus and a Poisson's ratio of 0.3 was chosen as suggested by Sigmund [14]. With these results, the response sensitivity of the TO to the variation of the load distribution could be demonstrated.

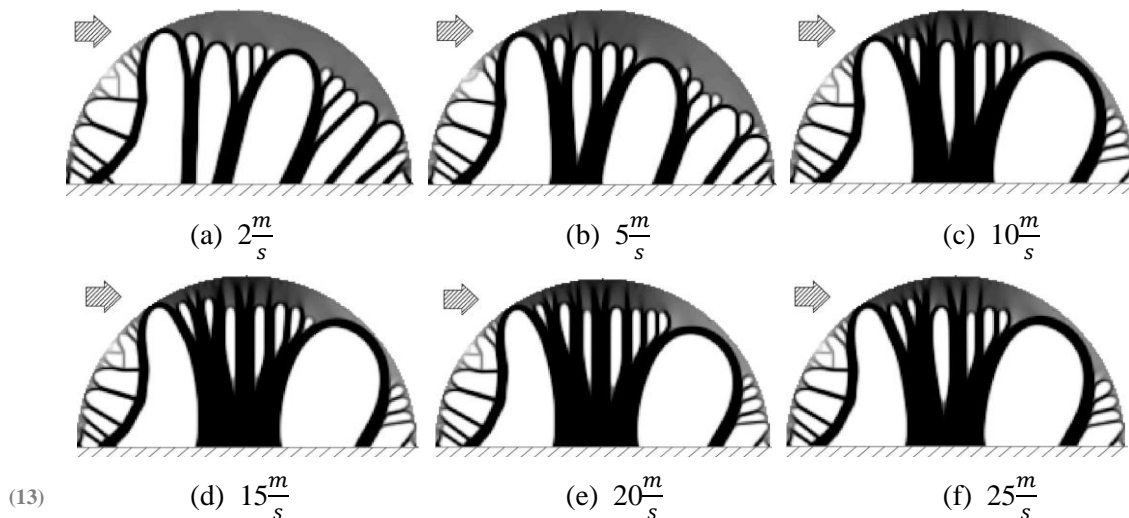|		
(a) $2\frac{m}{s}$	(b) $5\frac{m}{s}$	(c) $10\frac{m}{s}$
(d) $15\frac{m}{s}$	(e) $20\frac{m}{s}$	(f) $25\frac{m}{s}$

(13)

Figure 13: TO outcome for applied pressure coefficients of Figure 12 averaged over IW and 60s.

Nevertheless, structural design is based on characteristic loading derived from extreme value analysis rather than on mean load distributions. The recorded time series of the wind loading process allowed

to investigate the sensitivity of the TO to the stochastic variability of the applied loading. For this purpose, the recorded instantaneous pressure distributions were treated as individual load cases.
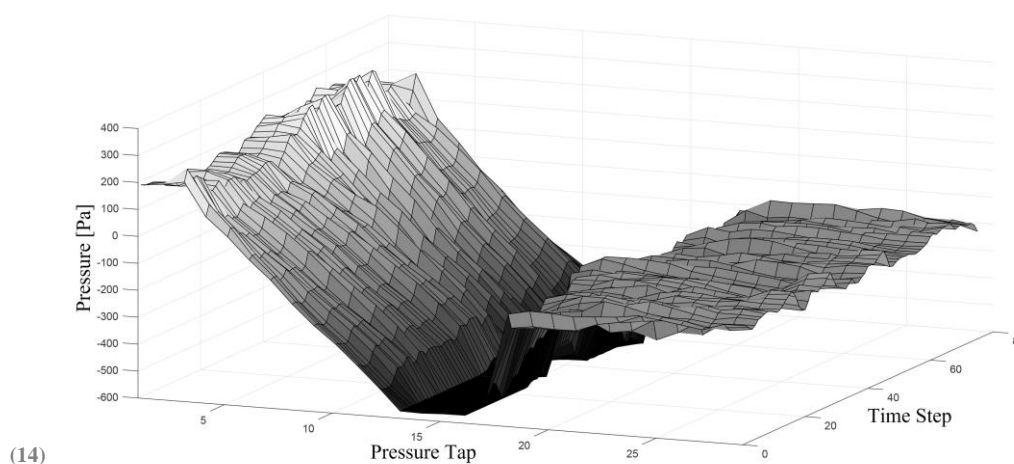

Figure 14: Linear interpolated pressure distribution for 75 subsequent time steps and $25\frac{m}{s}$ wind velocity.

Figure 14 illustrates the variability of the instantaneous pressure distributions of 75 subsequent time steps (equivalent to 0.1s) of the recorded data with a wind speed at reference height of $25\frac{m}{s}$. The TO solutions to the different load cases showed an almost insignificant variability, suggesting that wind turbulence and load fluctuation might be less significant for TO of load carrying structures.

However, for generalising the conclusion the sensitivity analysis needs to be expanded to all recorded data sets (restricted by computational power at time of initial study) and should be repeated for load simulations at higher turbulence levels reflecting rougher terrain surfaces. Here, a prevailing turbulence intensity of the along-wind flow component at the top of the model was about $I_u = 10\%$.

4. Conclusions and future work

The varied array of cases presented in this paper have demonstrated the value of Polar LWS as a study subject in its own right. The two different optimisation methods described have shown the feasibility of employing lightweight structures in Polar Regions in a larger scale than currently seen. However, further research work is needed in both cases, especially in regards to components design as well as physical prototyping and testing.

Furthermore, the field of Polar LWS offers a variety of study subjects worth to be explored, including: mechanical behaviour of lightweight materials under cryogenic temperatures, thermal insulation of LWS structures in cold climate, snowdrift loading patterns on surface structures, foundations on permafrost, among others.

The authors expect that the diversity of design methods and potential study subjects can motivate future researches to further explore the use of minimal impact LWS in Polar Regions.

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